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FORTRAN PROGRAM FOR CALCULATING AERODYNAMIC FORCES FROM PRESSURE OR VELOCITY DISTRIBUTIONS ON BLADE SECTIONS

by William D. McNally

Lewis Research Center

Cleveland, Ohio 44135

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16. Abstract

A FORTRAN IV program is presented which calculates aerodynamic forces on turbomachinery blade sections from distributions of pressure or velocity along the surfaces. Blade sections for which forces are calculated may have either one blade segment or two segments (tandem blades). Input includes blade surface coordinates, surface distributions of pressure or velocity, and several overall flow parameters. Surface angles may also be given as input, or may be computed by the program from spline curves. The program integrates pressure or velocity distributions to obtain components of force on the blade surfaces. Meridional and tangential forces and lift and drag forces are then computed. For tandem blade sections, ratios of forces on rear blade segments to forces on front blade segments are also given. The program is particularly useful in conjunction with existing ideal flow programs which allow the analytical study of blading.

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FORTRAN PROGRAM FOR CALCULATING AERODYNAMIC FORCES FROM PRESSURE OR VELOCITY DISTRIBUTIONS ON BLADE SECTIONS

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SUMMARY

A FORTRAN IV program is presented which calculates aerodynamic forces on turbomachinery blade sections from distributions of pressure or velocity along the surfaces. Forces due to pressure on either single blade sections or tandem blade sections may be calculated.

The program is designed to be used in conjunction with other existing programs which calculate blade surface and internal velocity distributions, streamlines, and boundary layers. Together these programs permit the analytical study of the flow through turbomachinery blading.

Input to this program includes blade surface coordinates, surface distributions of pressure or velocity, and several overall flow parameters. Spline curves are fitted to the surface coordinates to obtain surface angles; or these may be given as input. Pressure or velocity distributions are integrated around the blades using the trapezoidal rule to obtain components of force in the input coordinate system directions. Meridional and tangential forces, and lift and drag forces (due only to pressure) are computed from the integrated force components. For tandem blade sections, ratios of rear blade segment to front blade segment forces are also given.

Care must be exercised in the placement of points near blade leading and trailing edges. The points in these areas have high values of surface angle with corresponding large tangents used in the integrations. For this reason, input points must be more closely spaced in these regions.

This report includes a listing of the FORTRAN IV computer program, with an explanation of the input required and the output generated. Three tandem blades with different ratios of camber between the blade segments are analyzed with the program. A discussion is included concerning the placement of points on blade surfaces in order to obtain accurate results with the program. Running times are about 1/10 minute on IBM 7094 equipment. All parts of the program are in general FORTRAN IV code, and could be easily transferred to other IBM equipment.

INTRODUCTION

In the design, analysis, and comparison of blades for turbomachinery, it is desirable for a number of reasons to have knowledge of the aerodynamic forces acting on blade sections:

(1) Lift forces, or tangential forces, are directly related to the energy addition or work input.

(2) Blade surface forces due to pressure give a measure of each blade's "loading," where loading is thought of in terms of area under blade surface pressure profiles or total force on the blade section.

(3) For tandem blade sections, tangential forces provide a measure of "work-split" between the front and rear segments of the blades.

(4) Blade forces are used for the calculation of aerodynamic stresses and moments in the mechanical design process.

Forces on turbomachinery blading are of two kinds: pressure forces (mainly lift) and skin friction forces (mainly drag). In ideal flow, skin friction is neglected and the drag force is zero. So the only force is lift due to pressure. In real flow, skin friction exists and the drag is not zero. The component of drag due to skin friction can be computed with some degree of accuracy from boundary layer theory. Besides the skin friction drag, however, there is another type of drag called form drag or induced drag or pressure drag. This drag component due to pressure arises from the boundary layer displacing the free stream from the blade and modifying the ideal flow pressure distribution. Pressure drag is difficult to calculate (see refs. 1 and 2), especially from integration of real flow pressure profiles. On the other hand, pressure forces in the lift direction can be obtained from integration of ideal flow pressure profiles.

There are several methods available for obtaining forces on blade sections. One method is through the use of vector diagrams across the blade section with the assistance of empirical relations for fluid turning and loss. An alternate method, used more in the analysis of today's highly loaded blading which has not yet been tested, is to obtain forces analytically from the integration of blade surface pressure profiles.

This report describes a computer program developed to calculate aerodynamic forces on turbomachinery blading from given surface distributions of pressure or velocity. It is recommended primarily for use with ideal flow pressure distributions where forces in the drag direction can be neglected.

The force program described herein is particularly useful in conjunction with existing computer programs discussed in references 3 to 6. These programs calculate surface pressure distributions, free-stream and internal velocity distributions, streamlines, and boundary layers. Combining the results of all these programs allows the analytical study of the performance and two-dimensional flow through turbomachinery blading before it is studied experimentally in the laboratory.

This report presents a brief derivation of equations, a listing of the program, and a description of its input and output. Input to the program is easily obtained from the output of other programs for computing pressure or velocity distributions. Geometrical input consists of X-Y coordinates of blade surfaces in any two mutually perpendicular directions. Surface angles may be given as input or may be computed in the program from spline curves. Output consists of spline curve fits of surface coordinates and integrations of pressure along each blade surface, as well as integrated blade forces in desired directions. The report also includes numerical examples to illustrate typical input values and the form in which output is given. Internal variables used in the program are defined only if they pertain to input.

GENERAL DESCRIPTION OF PROGRAM

The program computes blade forces due to pressure distribution for either a single blade section or a tandem blade section (with two blade segments). Each blade section

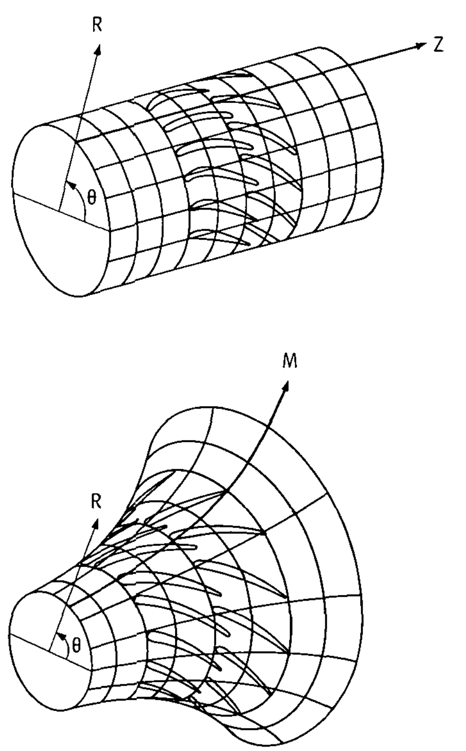
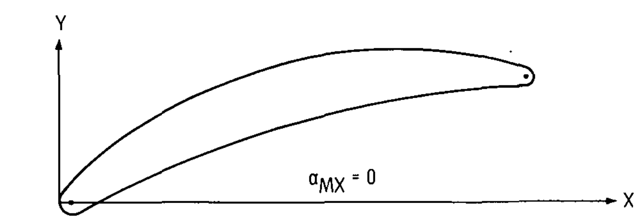
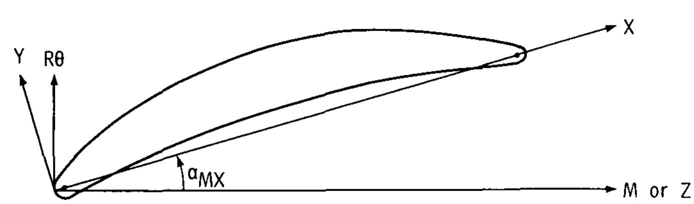


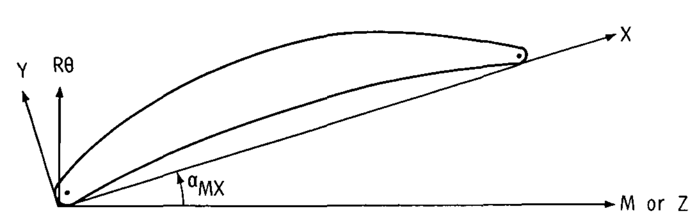
Figure 1. - Surfaces on which blade surface velocities are known.



(a) X axis coincident with M or Z axis.



(b) X axis through leading edge or trailing edge circle centers.



(c) X axis tangent to pressure surface leading edge and trailing edge radii.

Figure 2. - Typical variations in placement of X-Y input axes.

(i.e., each "cut" through a single or tandem blade) requires a separate set of input.

Input may be given on any plane on which blade pressures or velocities are known. Usually these are obtained on a cylindrical surface (Z-θ coordinates) or on an axisymmetric surface of revolution (M-θ coordinates) (see fig. 1). These unwrapped surfaces are the input planes for this program.

Blade geometry is defined by X-Y coordinates of each blade surface. The X and Y axes can be in any two mutually perpendicular directions, and are related to the Z-θ or M-θ directions by the input angle α_{MX} (see fig. 2). As figure 2 shows, the X and Y axes can be placed on the blade in any of the standard positions.

The second portion of the input, a description of the flow, is given by means of either blade surface static pressure or blade surface velocity distributions. Figure 3

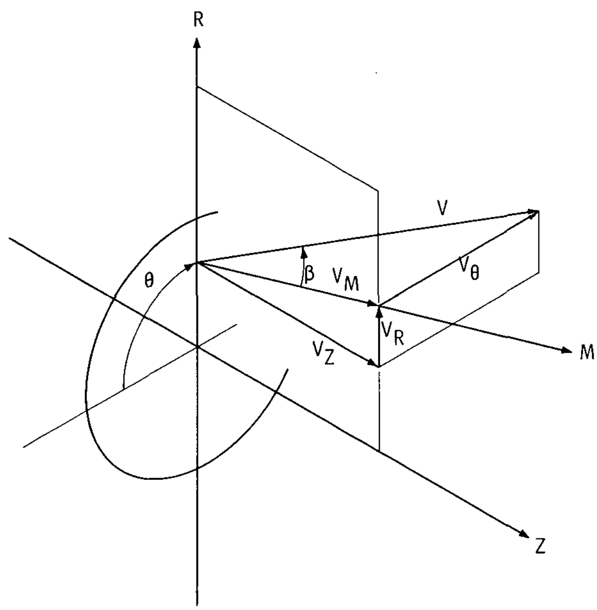


Figure 3. - Velocities in Z-R-θ and M-R-θ coordinate directions.

indicates the blade surface velocity components in the input planes: V_Z and V_θ on the cylindrical blade-to-blade plane, and V_M and V_θ on the general surface of revolution blade-to-blade plane.

Input is given on one blade surface at a time in the order indicated by figure 4. For single segment blades, only surfaces 1 and 2 are used. For a tandem blade, four surfaces are used and the front blade segment is entered before the rear blade segment.

The integration scheme requires blade surface angles (with respect to the X axis) at the X-Y input points (see fig. 5). These may either be given by the user as input, or be computed by the program by means of spline curve fits of the input geometry (refs. 7

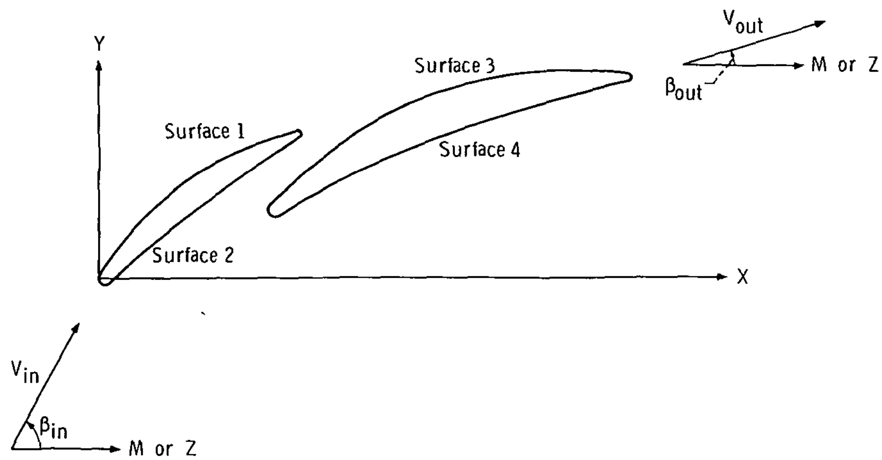


Figure 4. - Numbering of blade surfaces for input.

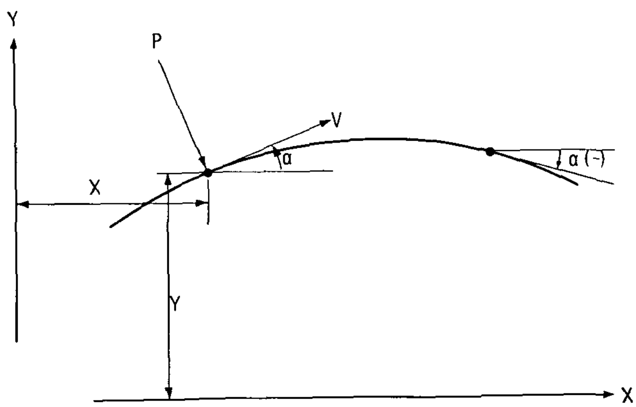


Figure 5. - Input parameters on typical surface.

and 8). The user may also give blade angles at a portion of the input points. In this case the program uses these input values where they are given, and uses computed angles from the spline curves at all the other points. In all cases spline fits of the blade surfaces are made; and slopes, curvatures, and angles are printed in the output.

Both blade surface pressures and velocities are printed as output. The relation between the two that is used in the program is Bernoulli's equation

$$\frac{\gamma}{\gamma - 1}\left(\frac{P'}{\rho'}\right)\left(\frac{P}{P'}\right)^{(\gamma-1)/\gamma} + \frac{V^2}{2} = \frac{\gamma}{\gamma - 1}\left(\frac{P'}{\rho'}\right) \tag{1}$$

Force components are obtained initially for each blade surface by integrating pressure distributions in the X and Y directions. On the suction surface the force in the X direction is given by

$$F_{X,s} = \sum P_s \, \Delta Y_s = \sum P_s \tan \alpha_s \, \Delta X_s \tag{2}$$

Using the average surface angles over dX increments, equation (2) becomes at each point i

$$\sum_{j=1}^{i} F_{X,s,j} = \sum_{j=1}^{i-1} F_{X,s,j} + \left(\frac{P_{s,i} + P_{s,i-1}}{2}\right) \tan\left(\frac{\alpha_{s,i} + \alpha_{s,i-1}}{2}\right)(X_{s,i} - X_{s,i-1}) \tag{3}$$

The force in the Y direction on the suction surface is

$$F_{Y,s} = \sum (-P_s) \Delta X_s \tag{4}$$

which becomes

$$\sum_{j=1}^{i} F_{Y,s,j} = \sum_{j=1}^{i-1} F_{Y,s,j} - \left(\frac{P_{s,i} + P_{s,i-1}}{2}\right)(X_{s,i} - X_{s,i-1}) \tag{5}$$

On the pressure surface the force in the X direction is given by

$$F_{X,p} = \sum (-P_p) \Delta Y_p = \sum (-P_p) \tan \alpha_p \, \Delta X_p \tag{6}$$

Again, using average surface angles, equation (6) becomes at each point

$$\sum_{j=1}^{i} F_{X,p,j} = \sum_{j=1}^{i-1} F_{X,p,j} - \left(\frac{P_{p,i} + P_{p,i-1}}{2}\right) \tan\left(\frac{\alpha_{p,i} + \alpha_{p,i-1}}{2}\right)(X_{p,i} - X_{p,i-1}) \tag{7}$$

The force in the Y direction on the pressure surface is

$$F_{Y,p} = \sum P_p \, \Delta X_p \tag{8}$$

which becomes

$$\sum_{j=1}^{i} F_{Y,p,j} = \sum_{j=1}^{i-1} F_{Y,p,j} + \left(\frac{P_{p,i} + P_{p,i-1}}{2}\right)(X_{p,i} - X_{p,i-1}) \tag{9}$$

After force components are obtained in the X and Y directions on each blade surface, they are rotated to the M and θ directions (see fig. 2) as follows

$$\left.\begin{aligned} F_M &= F_X \cos \alpha_{MX} - F_Y \sin \alpha_{MX} \\ F_\theta &= F_X \sin \alpha_{MX} + F_Y \cos \alpha_{MX} \end{aligned}\right\} \tag{10}$$

Finally force components are rotated to the lift-drag (L-D) directions (perpendicular and parallel to the direction of mean velocity V_{mean} at the mean flow angle β_{mean}, fig. 6) as follows

$$\left.\begin{aligned} F_D &= F_M \cos \beta_{mean} + F_\theta \sin \beta_{mean} \\ F_L &= -F_M \sin \beta_{mean} + F_\theta \cos \beta_{mean} \end{aligned}\right\} \tag{11}$$

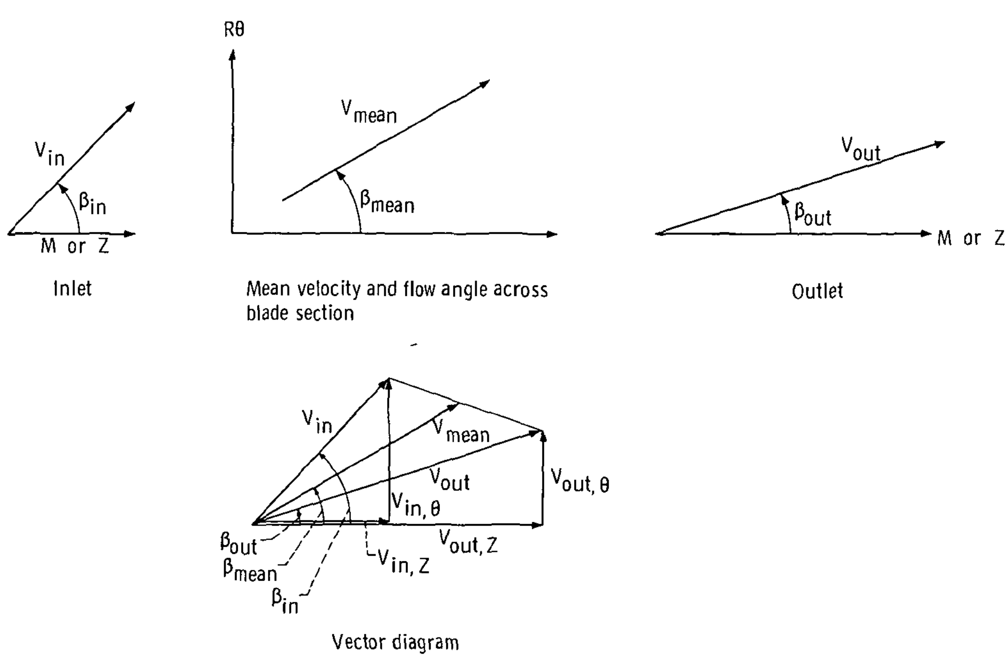


Figure 6. - Mean velocity vector and flow direction notation.

The mean flow angle across the blade section β_{mean} is computed by the formula (see fig. 6)

$$\beta_{mean} = \tan^{-1}\left(\frac{V_{in,\theta} + V_{out,\theta}}{V_{in,Z} + V_{out,Z}}\right) \tag{12}$$

After the calculation of force components (in various directions) on the blade surfaces, the components are summed for pressure and suction surfaces to obtain total forces in certain directions on each of the blade segments. In the X-Y directions these forces are obtained as follows

$$\left.\begin{aligned} F_X &= F_{X,s} + F_{X,p} \\ F_Y &= F_{Y,s} + F_{Y,p} \end{aligned}\right\} \tag{13}$$

Similar expressions are used in the M-θ and L-D directions.

After X-Y, M-θ, and L-D forces are computed for each blade segment, total forces and angles with respect to the M axis are computed for the segments. At this point the program is finished for a single segment blade section.

For tandem blades the program continues and adds together forces for both blade segments in all the principal directions. Ratios are also given for forces on the rear blade segment to forces in similar directions on the front blade segment.

For an ideal flow pressure distribution, the final drag force F_D for either a single segment blade or a tandem segment blade should be very close to zero. Inaccuracies in the input ideal flow pressure distribution and numerical inaccuracies in the program prevent F_D from being exactly zero. For a tandem blade, since the L and D directions are perpendicular and parallel to the direction of mean velocity across the overall blade section, F_D for either of the individual segments will not usually be zero. But F_D should be near zero when the segment contributions are summed for the overall blade section.

Output from the program consists of the following: (1) printing of all the input, (2) spline curve fit data for each surface, (3) summations from point to point of the surface pressure distributions to obtain force components, and (4) summed forces in all the principal directions.

The program is written entirely in FORTRAN IV and is run at NASA Lewis on the IBM 7094-7044 direct coupled system with a 32 768 word core ($77777_{(8)}$). The total program storage requirement is $22436_{(8)}$ of which $6335_{(8)}$ is used in the storage of variables. The program runs in 1/10 minute on IBM 7094 equipment.

At Lewis, the program is currently being used in conjunction with the programs of

references 3 to 5 to compute forces and evaluate work input and work splits on comparative blade designs. Ideal flow velocity distributions are being used as input.

NUMERICAL EXAMPLES

Three blade sections are included as numerical examples to illustrate the use of the program. All three are tandem blade sections with varying ratios of camber of the rear segment to camber of the front segment. These blades were generated by means of the program of reference 9. Table I contains some of the characteristic parameters of these blades. As table I indicates, the camber ratios vary from 1:1 to 3:1 (i.e., camber of rear blade segment three times camber of front blade segment). For all three blades the chord length of the rear blade segment is equal to the chord length of the front blade

TABLE I. - CHARACTERISTIC PARAMETERS OF THREE TANDEM

BLADES FOR NUMERICAL EXAMPLE

Tandem blade number	Camber ratio	Front blade camber, deg	Rear blade camber, deg	Total chord		Total camber, deg	Inlet blade angle, deg	Solidity, chord/spacing
				ft	m			
1	1.0	39.2	39.2	0.3333	0.1016	58.8	46.25	1.5
2	2.0	26.2	52.4	.3333	.1016	58.8	46.25	1.5
3	3.0	19.6	58.8	.3333	.1016	58.8	46.25	1.5

segment, and the overlap is 20 percent of the chord of the first blade segment. All three blade sections have a converging channel between blade segments, with the openings at the front and rear of the channel equal to 14 and 10 percent, respectively, of the front blade chord.

Figure 7 shows the three blade geometries superimposed. Figure 8 contains the three surface velocity distributions obtained by means of the program of reference 4. The input required for obtaining forces on blade number 2 is listed for illustration in table II; the variables are explained in the section Input Variables. Table III lists the important blade forces on each of the three tandem blades obtained by means of the program described herein. Lift, drag, and total force are also given for the entire tandem blade sections. Ideally, the drags would be zero, but these small components of drag do not noticeably affect the total forces on the blades. One of the principal points to notice on the table is the shift of forces from front to rear blade segment. The magnitude of these forces provides a measure of the work split F_θ and loading split F_{tot} between the two blade segments.

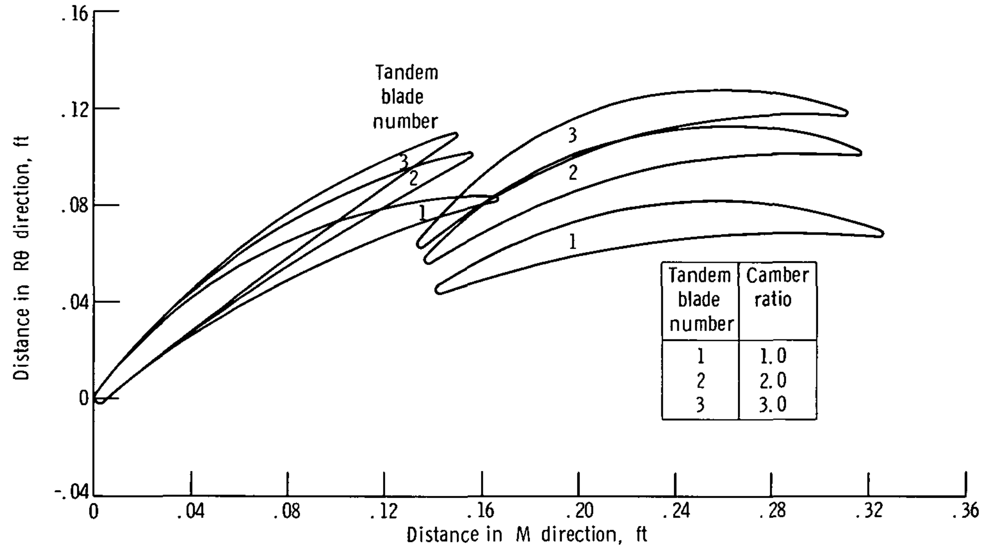


Figure 7. - Tandem blade section for numerical examples. (See blade parameters on table I.)

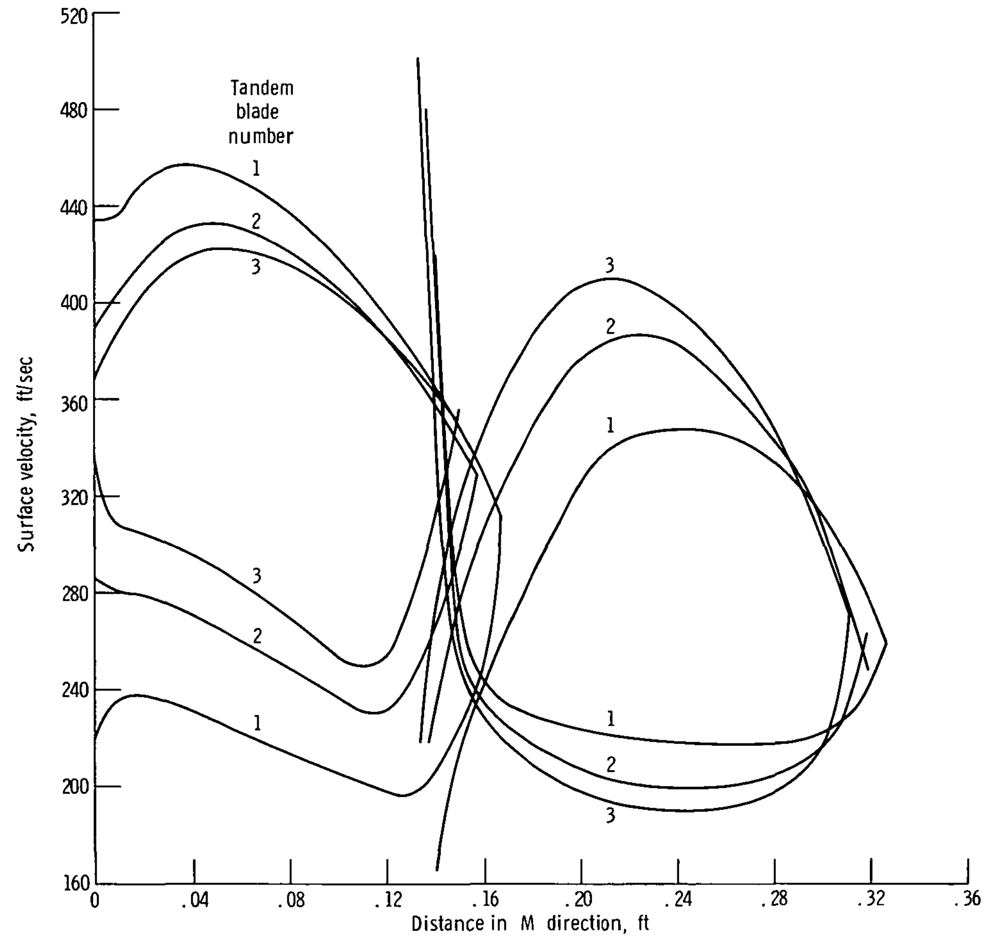


Figure 8. - Calculated surface velocity distributions for tandem blades used in numerical examples.

TABLE II. - INPUT FOR TANDEM BLADE NUMBER 2 OF NUMERICAL EXAMPLES

TANDEM DCA BLADE C2/C1=1.0 PH2/PH1=2.0 G/C1=.1 L/C1=.2 F=1.4

GAM	R	PTZ	TTZ		
1.400	1716.48	2080.00	520.00		
VRI	VRO	BETAI	BETAO	ALPHMX	
351.29100	249.63800	43.250	-1.000	0.	
KPV	KSURF	NSURF1	NSURF2	NSURF3	NSURF4
2	4	27	36	28	36

SUCTION SURFACE - FRONT BLADE

X1	Y1	V1	ANG1
0.	0.	389.0000	-0.
0.000400	0.001150	389.7000	-0.
0.001000	0.001920	390.5000	-0.
0.002000	0.003240	392.3000	-0.
0.005000	0.007050	397.1000	-0.
0.015164	0.019214	411.2000	-0.
0.025274	0.029916	422.7000	-0.
0.035384	0.039514	430.0000	-0.
0.045493	0.048186	433.4000	-0.
0.055603	0.056028	432.0000	-0.
0.065713	0.063142	429.0000	-0.
0.075822	0.069577	424.0000	-0.
0.085932	0.075391	417.7000	-0.
0.096041	0.080644	410.4000	-0.
0.106150	0.085368	401.0000	-0.
0.116260	0.089584	390.5000	-0.
0.126370	0.093328	377.9000	-0.
0.136480	0.096622	365.2000	-0.
0.143130	0.098534	353.7000	-0.
0.149770	0.100268	341.2000	-0.
0.152000	0.100810	336.9000	-0.
0.153100	0.101078	335.0000	-0.
0.154000	0.101270	333.0000	-0.
0.155000	0.101500	331.0000	-0.
0.155800	0.101300	329.3000	-0.
0.156200	C.100930	328.5000	-0.
0.156420	0.100088	328.0000	-0.

PRESSURE SURFACE - FRONT BLADE

X2	Y2	V2	ANG2
0.	0.	286.0000	-0.
0.000400	-0.001090	285.8000	-0.
0.001000	-0.001600	285.5000	-0.
0.002000	-0.001800	285.0000	-0.
0.003000	-0.001470	284.6000	-0.
0.004000	-0.000670	284.2000	-0.
0.005000	0.000150	283.9000	-0.
0.006000	0.000940	283.4000	-0.

TABLE II. - Continued. INPUT FOR TANDEM BLADE NUMBER 2

OF NUMERICAL EXAMPLES

0.008000	0.002580	282.9000	-0.
0.015164	0.008266	281.0000	-0.
0.025274	0.016086	278.1000	-0.
0.035384	0.023694	273.4000	-0.
0.045493	0.031025	268.2000	-0.
0.055603	0.038250	263.4000	-0.
0.065713	0.045199	258.5000	-0.
0.075822	0.051956	253.0000	-0.
0.080877	0.055250	249.6000	-0.
0.085932	0.058522	246.6000	-0.
0.090987	0.061731	243.3000	-0.
0.096041	0.064898	239.8000	-0.
0.101100	0.068021	236.9000	-0.
0.106150	0.071102	234.7000	-0.
0.111210	0.074120	232.4000	-0.
0.114000	0.075750	232.0000	-0.
0.116260	0.077095	232.2000	-0.
0.121320	0.080028	234.3000	-0.
0.126370	0.082918	239.9000	-0.
0.131430	0.085744	247.4000	-0.
0.136480	0.088549	258.5000	-0.
0.143130	0.092210	278.0000	-0.
0.149770	0.095752	300.0000	-0.
0.153000	0.097480	312.9000	-0.
0.155000	0.098440	321.1000	-0.
0.155800	0.098850	324.8000	-0.
0.156200	0.099240	326.8000	-0.
0.156420	0.100088	328.0000	-0.

SUCTION SURFACE - REAR BLADE

X3	Y3	V3	ANG3
0.136480	0.057651	218.0000	-0.
0.136800	0.058680	219.8000	-0.
0.137400	0.059400	223.0000	-0.
0.138000	0.060000	226.2000	-0.
0.139800	0.061838	235.0000	-0.
0.146450	0.068170	263.1100	-0.
0.153100	0.073822	287.4000	-0.
0.161460	0.080198	312.0000	-0.
0.171530	0.086864	333.2000	-0.
0.181600	0.092556	352.0000	-0.
0.191670	0.097393	369.1000	-0.
0.201740	0.101454	378.4000	-0.
0.211810	0.104782	384.0000	-0.
0.221880	0.107427	386.0000	-0.
0.231950	0.109435	385.5000	-0.
0.242030	0.110821	381.0000	-0.
0.252100	0.111592	373.3000	-0.
0.262170	0.111754	363.5000	-0.
0.272240	0.111320	353.0000	-0.
0.282310	0.110292	341.6000	-0.
0.292380	0.108662	324.2000	-0.
0.302450	0.106382	300.9000	-0.

TABLE II. - Concluded. INPUT FOR TANDEM BLADE NUMBER 2

OF NUMERICAL EXAMPLES

0.312520	0.103436	269.8000	-0.
0.315000	0.102600	259.5000	-0.
0.316000	0.102220	254.8000	-0.
0.316600	0.102000	252.0000	-0.
0.317200	0.101600	249.0000	-0.
0.317560	0.100725	247.4000	-0.

PRESSURE SURFACE - REAR BLADE

X4	Y4	V4	ANG4
0.136480	0.057651	480.0000	-0.
0.136800	0.056680	473.0000	-0.
0.137400	0.056120	458.0000	-0.
0.138000	0.055870	442.5000	-0.
0.139000	0.055900	418.4000	-0.
0.140000	0.056430	398.2000	-0.
0.141000	0.057110	379.2000	-0.
0.143000	0.058400	343.5000	-0.
0.146400	0.060540	290.0000	-0.
0.148000	0.061490	271.4000	-0.
0.150000	0.062670	257.0000	-0.
0.151600	0.063610	249.5000	-0.
0.153100	0.064450	245.6000	-0.
0.155000	0.065560	241.7000	-0.
0.161460	0.068999	233.4000	-0.
0.171530	0.074014	222.1000	-0.
0.181600	0.078540	215.5000	-0.
0.191670	0.082578	211.0000	-0.
0.201740	0.086169	207.0000	-0.
0.211810	0.089335	203.7000	-0.
0.221880	0.092098	200.8000	-0.
0.231950	0.094456	199.8000	-0.
0.242030	0.096411	199.5000	-0.
0.252100	0.097984	199.7000	-0.
0.262170	0.099174	200.8000	-0.
0.272240	0.100002	202.7000	-0.
0.282310	0.100491	205.6000	-0.
0.292380	0.100576	210.8000	-0.
0.302450	0.100300	219.9000	-0.
0.308000	0.100080	230.0000	-0.
0.312520	0.099662	242.3000	-0.
0.315000	0.099400	251.0000	-0.
0.316000	0.099290	255.0000	-0.
0.316600	0.099370	257.7000	-0.
0.317200	0.099790	260.1000	-0.
0.317560	0.100725	261.3000	-0.

TABLE III. - TANDEM BLADE FORCES

Tandem blade number	Front blade forces, lbf/ft (N/m) of span			Rear blade forces, lbf/ft (N/m) of span			Total tandem blade forces, lbf/ft (N/m) of span					Mean flow angle across blade section, β_{mean}, deg
	F_M	F_θ	F_{tot}	F_M	F_θ	F_{tot}	F_M	F_θ	F_{tot}	F_L	F_D	
1	-13.13 (-191.62)	23.20 (338.58)	26.65 (388.93)	-0.72 (-10.51)	8.84 (129.01)	8.87 (129.45)	-13.85 (-202.13)	32.04 (467.59)	34.90 (509.33)	34.90 (509.33)	0.15 (2.19)	23.62
2	-11.36 (-165.79)	16.43 (239.78)	19.97 (291.44)	-2.79 (-40.72)	13.50 (197.02)	13.78 (201.10)	-14.15 (-206.51)	29.93 (436.80)	33.10 (483.06)	33.10 (483.06)	-0.14 (-2.04)	25.06
3	-9.74 (-142.14)	12.95 (188.99)	16.21 (236.57)	-5.25 (-76.62)	16.79 (245.03)	17.59 (256.71)	-14.99 (-218.76)	29.74 (434.02)	33.31 (486.12)	33.30 (485.98)	-0.75 (-10.95)	25.46

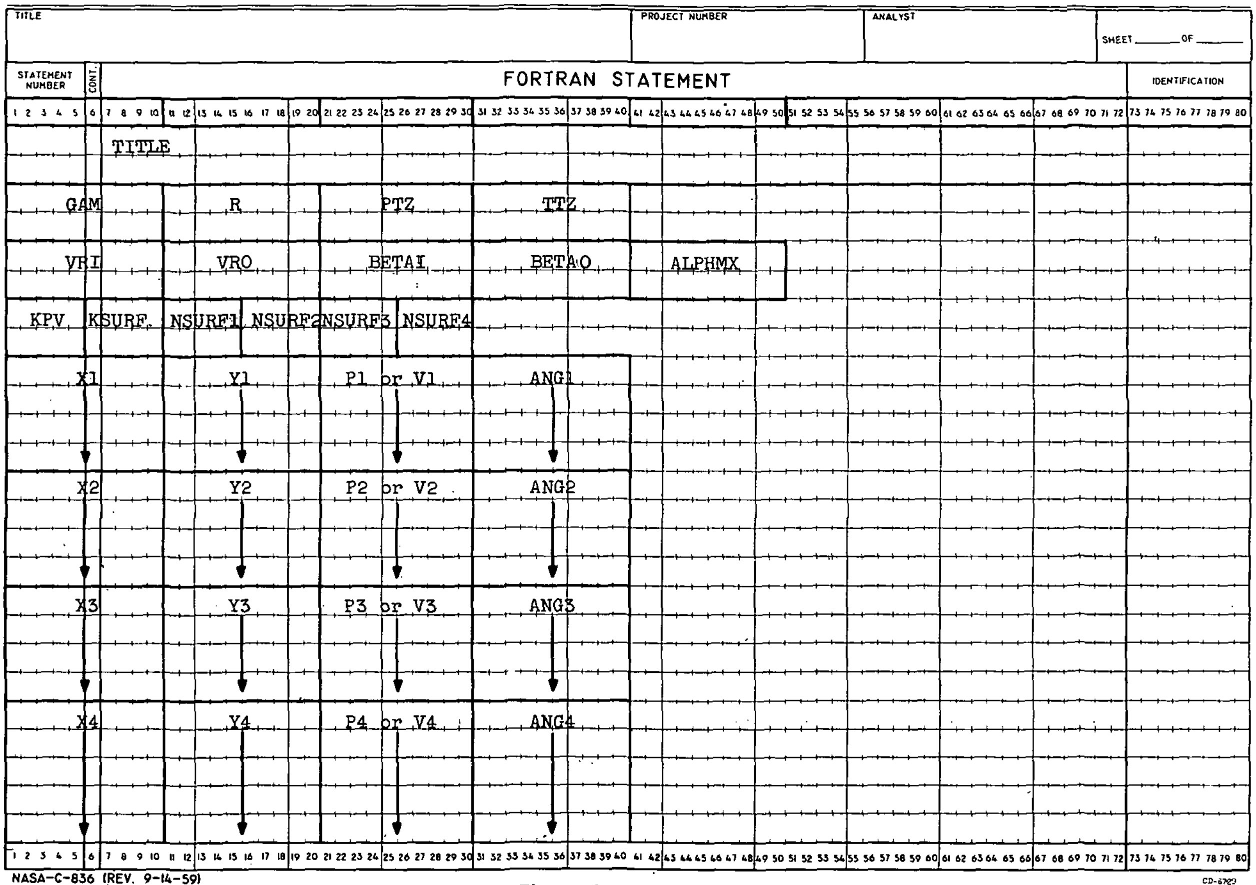


Figure 9. - Input form.

INPUT

Figure 9 shows the input variables as they are punched on data cards. The first input card is for a title which identifies the data deck and is printed on the output. The user may type whatever information he wishes in any of the columns of this card. The remaining cards are for input data; the input variables are defined in the next section.

Input Variables

GAM — specific heat ratio, γ

R — gas constant, R, (ft)(lbf)/(slug)(^{o}R); J/(kg)(K)

PTZ — inlet or upstream relative total pressure, P', (lbf)/(ft^2); N/(m)^2

TTZ	inlet or upstream relative total temperature, T', ^{o}R; K
VRI	inlet or upstream flow velocity relative to blade row, V_{in}, ft/sec; m/sec (figs. 4 and 6)
VRO	outlet or downstream flow velocity relative to blade row, V_{out}, ft/sec; m/sec (figs. 4 and 6)
BETAI	inlet or upstream relative flow angle, β_{in}, deg (figs. 4 and 6)
BETAO	outlet or downstream relative flow angle, β_{out}, deg (figs. 4 and 6) BETAO is positive if rotation from the M or Z axis to V_{out} is counterclockwise; negative if rotation is clockwise.
ALPHMX	angle between meridional axis and X axis of input, α_{MX}, deg (fig. 2) $-90^{o} < \alpha_{MX} < 90^{o}$; ALPHMX is positive if rotation from the M or Z axis to the X axis is counterclockwise; negative if rotation is clockwise.
KPV	integer (1 or 2) indicating whether pressures (1) or velocities (2) are used to input flow conditions on the blade surfaces
KSURF	integer (2 or 4) indicating whether input is given for a single segment blade section (two surfaces) or for a tandem blade section (four surfaces)
NSURF1(NSURF2, NSURF3, NSURF4)	integer number of input points on surface 1 (surfaces 2 to 4) If KSURF = 2, NSURF3 and NSURF4 should be zero.
X1(X2, X3, X4)	array of X coordinates of input points on surface 1 (surfaces 2 to 4), X, ft; m (figs. 2 and 5)
Y1(Y2, Y3, Y4)	array of Y coordinates of input points on surface 1 (surfaces 2 to 4), Y, ft; m (figs. 2 and 5) The X and Y coordinates on all surfaces are given with respect to the same X-Y origin. There is not a separate origin for each blade segment (fig. 4).
P1(P2, P3, P4)	array of static pressures at the input points on surface 1 (surfaces 2 to 4), P, lbf/ft^2; N/m^2 (fig. 5)
V1(V2, V3, V4)	array of relative surface or free-stream velocities at the input points on surface 1 (surfaces 2 to 4), V, ft/sec; m/sec (see fig. 5) Either pressure P or velocity V is used to input flow conditions on the blade surfaces. KPV indicates which of the two is used in a set of input data.

ANG1(ANG2, ANG3, ANG4) array of surface angles with respect to the X axis at the input points on surface 1 (surfaces 2 to 4), α, deg (see fig. 5) The angle α is positive if rotation from the X axis to the tangent to the surface is counterclockwise; negative if rotation is clockwise. Angles may be given at all points, at no points, or at only some of the points. If any angles are given, spline curve results will be overriden at the points where angles are given as input.

All the information for a single input point (X, Y, P or V, and α) is given on a single data card (see fig. 9). For a single blade (KSURF = 2), NSURF3 and NSURF4 are set to zero, and no cards are given for blade surfaces 3 and 4 (X3, Y3, etc., and X4, Y4, etc.)

Placement of Points for Accurate Results

In order to obtain accurate values for force, particularly in the drag direction, several factors have to be kept in mind. First, consider the trapezoidal integration scheme. It approximates areas under a curve of the function to be integrated by areas of trapezoids. In order to achieve accuracy, sufficient points are needed in regions where the slope of the function is changing rapidly. The function to be integrated in this program depends upon pressure and surface angle, and these change most rapidly around the leading and trailing edges of the blades. The computer program which generates the ideal flow pressure or velocity distribution may not give enough points in these regions. If that is the case, plots must be made of the blade leading and trailing edges and the pressure or velocity distributions in these regions in order to interpolate data for input. This procedure had to be followed for the blades used in the numerical examples of this report. Figure 10 shows this plot for the front blade segment of blade number 2 of the numerical examples. The circled points indicate where surface velocities were available from the ideal flow program of reference 4. Points indicated by triangles were added for use in this program.

A second factor is that the velocities plotted in figure 10 are in error very close to the leading edge of the blade. The velocity distributions do not include the deceleration to zero at the stagnation point, nor the peak velocities occurring due to rapid accelerations around the leading edge radius. Figure 10 merely contains enlarged portions of the plot of figure 8 which represents the output of the programs of reference 4. The very local peaks about the leading and trailing edges of this blade do not affect the overall loading significantly, and can be neglected. If need be, they can be calculated using reference 5 and included in this analysis.

A third point is that the force in the X direction (generally close to the drag force

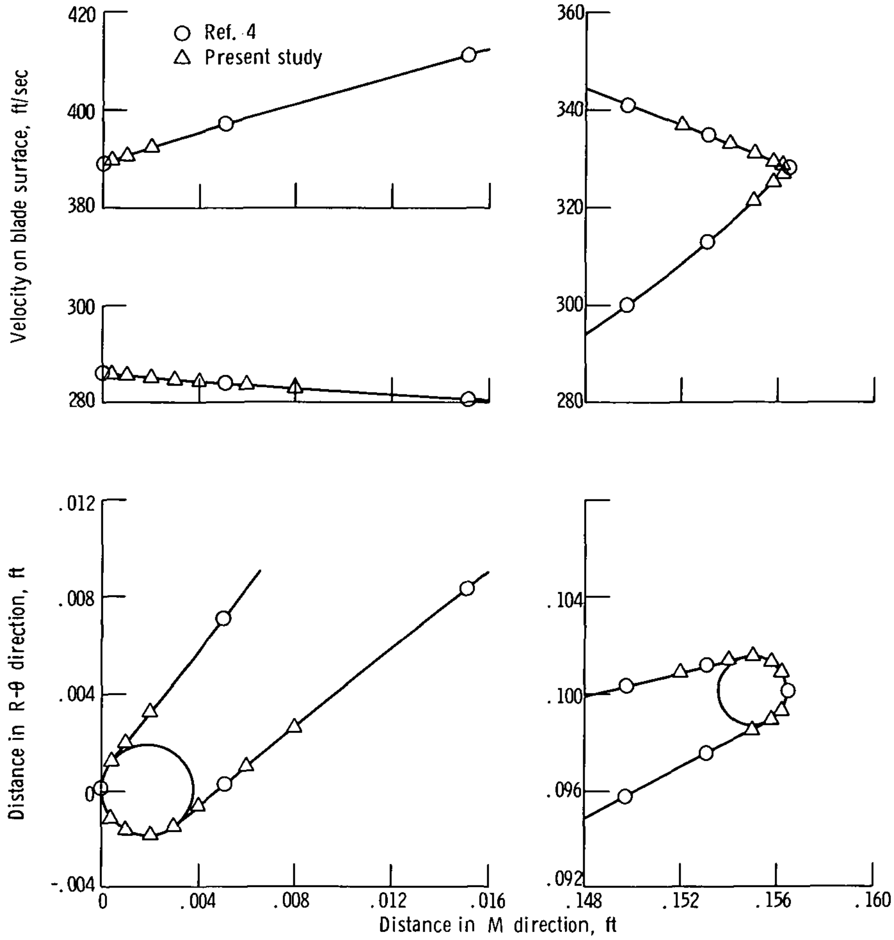


Figure 10. - Leading and trailing edge surfaces and velocities for front blade segment of tandem blade number 2.

direction) is very sensitive to the blade surface angles at the input points, particularly around the leading and trailing edges. For example, changing the number of points around a leading edge can alter the drag force as much as 25 percent while the lift force remains essentially unchanged. This is why the leading edge must be described in detail as it has been on figure 10. In general, 25 to 35 points has been found to be adequate for describing most blade surfaces, with about one-third of these concentrated near the leading and trailing edges.

Finally, attention must be given to the spline curve fits of the blade geometry. If blade surface angles are not supplied by the user, these angles are obtained from the spline fits through the blade surface coordinates. Since spline curves pass exactly through the fitted points (see refs. 7 and 8), these points must be given accurately or else a "wavy" curve will result. And the angles on a "wavy" curve are greatly in error. Since the forces computed in this program depend heavily on these angles, it is impor-

tant that the curve fits be accurate. The user should always check the spline curve output to the program. If a particular curve is not smooth (i.e., its angles do not increase or decrease smoothly, or the curvature changes sign radically from point to point), one of two changes should be made. Either the input points should be adjusted so that the curve fit improves, or input angles should be supplied in that particular region by the user. In the numerical example, input angles could be given for the relatively poor spline angles (47.26 and 40.37) at the third input points on surfaces 1 and 3 of example tandem blade number 2 (see table IV).

TABLE IV. - SELECTED OUTPUT FOR TANDEM BLADE NO. 2 OF NUMERICAL EXAMPLES

TANDEM DCA BLADE   C2/C1=1.0   PH2/PH1=2.0   G/C1=.1   L/C1=.2   F=1.4

GAM	R	PTZ	TTZ		
1.400	1716.48	2080.00	520.00		
VRI	VRO	BETAI	BETAO	ALPHMX	
351.29100	249.63800	43.250	-1.000	0.	
KPV	KSURF	NSURF1	NSURF2	NSURF3	NSURF4
2	4	27	36	28	36

SUCTION SURFACE - FRONT BLADE

X1	Y1	V1	ANG1
0.	0.	389.0000	-0.
0.000400	0.001150	389.7000	-0.
0.001000	0.001920	390.5000	-0.
0.002000	0.003240	392.3000	-0.
0.005000	0.007050	397.1000	-0.
0.015164	0.019214	411.2000	-0.
0.025274	0.029916	422.7000	-0.
0.035384	0.039514	430.0000	-0.
⋮	⋮	⋮	⋮

SURFACE 1 - SPLINE FIT OF X-Y

X	Y	SLOPE	SEC. DERIV.	CURVATURE	SPLINE ANGLE	INPUT ANGLE
0.	0.	4.06782	-7156.91138	-97.36791	76.1887	-0.
0.000400	0.001150	1.92075	-3578.45569	-352.40246	62.4971	-0.
0.001000	0.001920	1.08205	782.79342	244.74290	47.2567	-0.
0.002000	0.003240	1.40451	-137.86566	-26.89928	54.5494	-0.
0.005000	0.007050	1.20778	6.71066	1.74060	50.3764	-0.
0.015164	0.019214	1.14066	-19.91772	-5.70605	48.7594	-0.
0.025274	0.029916	0.99503	-8.89076	-3.16687	44.8573	-0.
0.035384	0.039514	0.90295	-9.32564	-3.81286	42.0804	-0.
0.045493	0.048186	0.81479	-8.11654	-3.78171	39.1727	-0.
0.055603	0.056028	0.73846	-6.98326	-3.63522	36.4443	-0.
0.065713	0.063142	0.66936	-6.68513	-3.83650	33.7969	-0.
0.075822	0.069577	0.60475	-6.09907	-3.82139	31.1633	-0.
0.085932	0.075391	0.54656	-5.41140	-3.65622	28.6593	-0.
0.096041	0.080644	0.49314	-5.15797	-3.72113	26.2497	-0.
0.106150	0.085368	0.44171	-5.01593	-3.83919	23.8317	-0.
0.116260	0.089584	0.39297	-4.62750	-3.73078	21.4532	-0.
0.126370	0.093328	0.34844	-4.18121	-3.52092	19.2103	-0.
0.136480	0.096622	0.30171	-5.06328	-4.44302	16.7890	-0.

TABLE IV. - Continued. SELECTED OUTPUT FOR TANDEM BLADE NO. 2 OF NUMERICAL EXAMPLES

0.143130	0.098534	0.27598	-2.67535	-2.39642	15.4283	-0.
0.149770	0.100268	0.24036	-8.05169	-7.40112	13.5154	-0.
0.152000	0.100810	0.25740	23.33112	21.19065	14.4346	-0.
0.153100	0.101078	0.20328	-121.73237	-114.55878	11.4904	-0.
0.154000	0.101270	0.28822	310.50212	275.47210	16.0783	-0.
0.155000	0.101500	-0.04170	-970.35752	-967.83167	-2.3880	-0.
0.155800	0.101300	-0.27845	378.49150	338.38385	-15.5598	-0.
0.156200	0.100930	-2.29381	-10455.30090	-667.28804	-66.4449	-0.
0.156420	0.100088	-5.74407	-20910.60181	-105.50107	-80.1242	-0.

SURFACE 2 - SPLINE FIT OF X-Y

X	Y	SLOPE	SEC. DERIV.	CURVATURE	SPLINE ANGLE	INPUT ANGLE
0.	0.	-4.04298	7907.87189	109.46437	-76.1072	-0.
0.000400	-0.001090	-1.67062	3953.93594	535.68018	-59.0961	-0.
0.001000	-0.001600	-0.39495	298.29909	240.00753	-21.5514	-0.
0.002000	-0.001800	0.04074	573.08138	571.65733	2.3331	-0.
0.003000	-0.001470	0.62197	589.37535	360.86779	31.8805	-0.
0.004000	-0.000670	0.86137	-110.58288	-48.09860	40.7406	-0.
0.005000	0.000150	0.79255	-27.04368	-13.01748	38.3988	-0.
0.006000	0.000940	0.79841	38.75761	18.49696	38.6043	-0.
0.008000	0.002580	0.82442	-12.75106	-5.85749	39.5028	-0.
0.015164	0.008266	0.77791	-0.23308	-0.11461	37.8797	-0.
0.025274	0.016086	0.76583	-2.15563	-1.07873	37.4461	-0.
0.035384	0.023694	0.73679	-3.58913	-1.87282	36.3826	-0.
0.045493	0.031025	0.72014	0.29372	0.15695	35.7591	-0.
0.055603	0.038250	0.70216	-3.85091	-2.11088	35.0749	-0.
0.065713	0.045199	0.67717	-1.09174	-0.61978	34.1047	-0.
0.075822	0.051956	0.65642	-3.01410	-1.76096	33.2816	-0.
0.080877	0.055250	0.64968	0.34737	0.20484	33.0109	-0.
0.085932	0.058522	0.64161	-3.54143	-2.11147	32.6844	-0.
0.090987	0.061731	0.63019	-0.97438	-0.59002	32.2188	-0.
0.096041	0.064898	0.62198	-2.27666	-1.39396	31.8806	-0.
0.101100	0.068021	0.61375	-0.97385	-0.60288	31.5397	-0.
0.106150	0.071102	0.60525	-2.39509	-1.49966	31.1843	-0.
0.111210	0.074120	0.58489	-5.65009	-3.63394	30.3231	-0.
0.114000	0.075750	0.59078	9.87256	6.30086	30.5739	-0.
0.116260	0.077095	0.59268	-8.19776	-5.21896	30.6542	-0.
0.121320	0.080028	0.57432	0.94288	0.61483	29.8697	-0.
0.126370	0.082918	0.56581	-4.31413	-2.84422	29.5016	-0.
0.131430	0.085744	0.55479	-0.04071	-0.02722	29.0211	-0.
0.136480	0.088549	0.55686	0.85919	0.57298	29.1116	-0.
0.143130	0.092210	0.53501	-7.43088	-5.09402	28.1471	-0.
0.149770	0.095752	0.55496	13.44039	8.98485	29.0284	-0.
0.153000	0.097480	0.47333	-63.98429	-47.24755	25.3296	-0.
0.155000	0.098440	0.55733	147.97984	98.62603	29.1320	-0.
0.155800	0.098850	0.36366	-632.15340	-524.70058	19.9841	-0.
0.156200	0.099240	2.32413	10434.53406	644.23296	66.7193	-0.
0.156420	0.100088	5.76754	20869.06812	104.04876	80.1636	-0.

SURFACE 3 - SPLINE FIT OF X-Y

X	Y	SLOPE	SEC. DERIV.	CURVATURE	SPLINE ANGLE	INPUT ANGLE
0.136480	0.057651	4.56656	-10132.05212	-99.17828	77.6482	-0.
0.136800	0.058680	2.13486	-5066.02606	-386.66180	64.9010	-0.
0.137400	0.059400	0.85009	783.42208	346.49924	40.3674	-0.
0.138000	0.060000	1.06480	-67.71216	-21.72389	46.7975	-0.
0.139800	0.061838	0.99468	-10.19747	-3.63424	44.8472	-0.
0.146450	0.068170	0.90109	-17.95037	-7.35954	42.0216	-0.
0.153100	0.073822	0.80728	-10.26168	-4.83414	38.9133	-0.
0.161460	0.080198	0.71637	-11.48868	-6.17211	35.6165	-0.
.	.	.	.	.	.	.
.	.	.	.	.	.	.
.	.	.	.	.	.	.
.	.	.	.	.	.	.

TABLE IV. - Continued. SELECTED OUTPUT FOR TANDEM BLADE NO. 2 OF NUMERICAL EXAMPLES

SURFACE 4 - SPLINE FIT OF X-Y

X	Y	SLOPE	SEC. DERIV.	CURVATURE	SPLINE ANGLE	INPUT ANGLE
0.136480	0.057651	-4.40039	10245.14673	111.49134	-77.1568	-0.
0.136800	0.056680	-1.94155	5122.57336	491.76962	-62.7492	-0.
0.137400	0.056120	-0.45367	-162.95498	-123.06826	-24.4023	-0.
0.138000	0.055870	-0.29377	695.94306	614.67782	-16.3714	-0.
0.139000	0.055900	0.32957	550.75204	471.82649	18.2409	-0.
0.140000	0.056430	0.65547	101.04542	59.11178	33.2438	-0.
⋮	⋮	⋮	⋮	⋮	⋮	⋮

SURFACE 1 - INTEGRATION OF (AVERAGE PRESSURE*TAN(AVERAGE ANGLE)) TO GET FX1

X	PRESSURE	VELOCITY	INTEGRAND1	INTEGRAND2	SUM
0.	1908.95782	389.00000	0.	5063.37781	0.
0.000400	1908.36055	389.70000	5061.79358	2712.99512	2.02503
0.001000	1907.67673	390.50000	2712.02298	2347.65125	3.65254
0.002000	1906.13377	392.30000	2345.75244	2480.79465	5.99924
0.005000	1901.98886	397.10000	2475.40012	2232.29367	13.43353
0.015164	1889.56056	411.20000	2217.70703	2012.76736	36.04844
0.025274	1879.14795	422.70000	2001.67581	1781.30598	56.34145
0.035384	1872.41116	430.00000	1774.91997	1606.35677	74.31817
0.045493	1869.24011	433.40000	1603.63629	1450.37564	90.54308
0.055603	1870.54842	432.00000	1451.39078	1315.64914	105.21151
0.065713	1873.33980	429.00000	1317.61246	1192.53510	118.52264
0.075822	1877.95544	424.00000	1195.47333	1080.36482	130.59283
0.085932	1883.70537	417.70000	1083.67268	978.69334	141.53204
0.096041	1890.27571	410.40000	982.10702	883.08479	151.44290
0.106150	1898.58884	401.00000	886.96844	791.95667	160.38964
0.116260	1907.67673	390.50000	795.74750	706.87220	168.41548
0.126370	1918.30307	377.90000	710.80969	623.28059	175.58186
0.136480	1928.70177	365.20000	626.65925	557.00500	181.90031
0.143130	1937.84424	353.70000	559.64532	500.14394	185.61317
0.149770	1947.48326	341.20000	502.63171	484.65864	188.94238
0.152000	1950.72658	336.90000	485.46579	449.01623	190.02407
0.153100	1952.14780	335.00000	449.34336	478.92900	190.51817
0.154000	1953.63586	333.00000	479.29408	234.51831	190.94937
0.155000	1955.11591	331.00000	234.69597	-308.74772	191.18397
0.155800	1956.36755	329.30000	-308.94538	-1700.78606	190.93689
0.156200	1956.95448	328.50000	-1701.29631	-6516.48517	190.25648
0.156420	1957.32066	328.00000	-6517.70447	0.	188.82271

SURFACE 1 - INTEGRATION OF (-P) TO GET FY1

X	PRESSURE	VELOCITY	INTEGRAND1	INTEGRAND2	SUM
0.	1908.95782	389.00000	-1908.95782	-1908.95782	0.
0.000400	1908.36055	389.70000	-1908.36055	-1908.36055	-0.76346
0.001000	1907.67673	390.50000	-1907.67673	-1907.67673	-1.90827
0.002000	1906.13377	392.30000	-1906.13377	-1906.13377	-3.81518
0.005000	1901.98886	397.10000	-1901.98886	-1901.98886	-9.52736
0.015164	1889.56056	411.20000	-1889.56056	-1889.56056	-28.79602
0.025274	1879.14795	422.70000	-1879.14795	-1879.14795	-47.84684
0.035384	1872.41116	430.00000	-1872.41116	-1872.41116	-66.81097
⋮	⋮	⋮	⋮	⋮	⋮

SURFACE 2 - INTEGRATION OF (-AVERAGE PRESSURE*TAN(AVERAGE ANGLE)) TO GET FX2

X	PRESSURE	VELOCITY	INTEGRAND1	INTEGRAND2	SUM
0.	1986.24275	286.00000	0.	4819.36914	0.
0.000400	1986.37170	285.80000	4819.68201	1685.97951	1.92781
0.001000	1986.56491	285.50000	1686.14349	336.32727	2.93945
0.002000	1986.88658	285.00000	336.38173	-611.50432	3.27580

0.003000	1987.14349	284.60000	-611.58339	-1460.26328	2.66426
0.004000	1987.40013	284.20000	-1460.45187	-1642.34860	1.20390
0.005000	1987.59236	283.90000	-1642.50746	-1581.08849	-0.43853
0.006000	1987.91229	283.40000	-1581.34297	-1612.85777	-2.01974
0.008000	1988.23177	282.90000	-1613.11697	-1592.37494	-5.24572
0.015164	1989.44083	281.00000	-1593.34328	-1535.55826	-16.65696
0.025274	1991.27148	278.10000	-1536.97127	-1495.86957	-32.18860
0.035384	1994.20064	273.40000	-1498.06998	-1452.64209	-47.32296
0.045493	1997.38667	268.20000	-1454.96291	-1420.35960	-62.01945
0.055603	2000.27650	263.40000	-1422.41458	-1379.37242	-76.38967
0.065713	2003.17566	258.50000	-1381.37166	-1335.60754	-90.34523
0.075822	2006.36848	253.00000	-1337.73634	-1310.24495	-103.85765
0.080877	2008.30965	249.60000	-1311.51262	-1296.63350	-110.48414
0.085932	2010.00174	246.60000	-1297.72597	-1278.12712	-117.04138
0.090987	2011.84050	243.30000	-1279.29636	-1259.56548	-123.50527
0.096041	2013.76498	239.80000	-1260.77036	-1244.21977	-129.87416
0.101100	2015.33940	236.90000	-1245.19255	-1228.33456	-136.17113
0.106150	2016.52159	234.70000	-1229.05510	-1199.88022	-142.37604
0.111210	2017.74619	232.40000	-1200.60889	-1186.10077	-148.44927
0.114000	2017.95802	232.00000	-1186.22530	-1194.08492	-151.75867
0.116260	2017.85213	232.20000	-1194.02226	-1177.33980	-154.45723
0.121320	2016.73538	234.30000	-1176.68823	-1149.65436	-160.41292
0.126370	2013.71034	239.90000	-1147.92992	-1128.25554	-166.21432
0.131430	2009.55240	247.40000	-1125.92589	-1116.95712	-171.91739
0.136480	2003.17566	258.50000	-1113.41278	-1093.49748	-177.54908
0.143130	1991.33432	278.00000	-1087.03351	-1085.15915	-184.79934
0.149770	1977.00883	300.00000	-1077.35260	-1015.12959	-191.97888
0.153000	1968.13889	312.90000	-1010.57516	-1012.82432	-195.25039
0.155000	1962.32207	321.10000	-1009.83092	-896.68433	-197.27305
0.155800	1959.65224	324.80000	-895.46435	-1850.02377	-197.98991
0.156200	1958.19746	326.80000	-1848.65039	-6586.04169	-198.72964
0.156420	1957.32066	328.00000	-6583.09271	0.	-200.17825

SURFACE 2 - INTEGRATION OF (P) TO GET FY2

X	PRESSURE	VELOCITY	INTEGRAND1	INTEGRAND2	SUM
0.	1986.24275	286.00000	1986.24275	1986.24275	0.
0.000400	1986.37170	285.80000	1986.37170	1986.37170	0.79452
0.001000	1986.56491	285.50000	1986.56491	1986.56491	1.98640
0.002000	1986.88658	285.00000	1986.88658	1986.88658	3.97313
0.003000	1987.14349	284.60000	1987.14349	1987.14349	5.96014
0.004000	1987.40013	284.20000	1987.40013	1987.40013	7.94742
0.005000	1987.59236	283.90000	1987.59236	1987.59236	9.93491
⋮	⋮	⋮	⋮	⋮	⋮

SURFACE 3 - INTEGRATION OF (AVERAGE PRESSURE*TAN(AVERAGE ANGLE)) TO GET FX3

X	PRESSURE	VELOCITY	INTEGRAND1	INTEGRAND2	SUM
0.136480	2025.15070	218.00000	0.	5974.31323	0.
0.136800	2024.24997	219.80000	5971.65601	2650.88300	1.91136
0.137400	2022.63115	223.00000	2648.76303	1924.94296	3.50125
0.138000	2020.98991	226.20000	1923.38100	2079.85095	4.65575
0.139800	2016.36099	235.00000	2075.08719	1909.07281	8.39519
0.146450	2000.44951	263.11000	1894.00795	1706.58331	21.04044
0.153100	1985.33784	287.40000	1693.69154	1510.50345	32.34635
0.161460	1968.76892	312.00000	1497.89732	1304.13586	44.92146
⋮	⋮	⋮	⋮	⋮	⋮

TABLE IV. - Continued. SELECTED OUTPUT FOR TANDEM BLADE NO. 2 OF NUMERICAL EXAMPLES

SURFACE 3 - INTEGRATION OF (-P) TO GET FY3

X	PRESSURE	VELOCITY	INTEGRAND1	INTEGRAND2	SUM
0.136480	2025.15070	218.00000	-2025.15070	-2025.15070	0.
0.136800	2024.24997	219.80000	-2024.24997	-2024.24997	-0.64791
0.137400	2022.63115	223.00000	-2022.63115	-2022.63115	-1.86197
0.138000	2020.98991	226.20000	-2020.98991	-2020.98991	-3.07506
0.139800	2016.36099	235.00000	-2016.36099	-2016.36099	-6.70867
0.146450	2000.44951	263.11000	-2000.44951	-2000.44951	-20.06457
0.153100	1985.33784	287.40000	-1985.33784	-1985.33784	-33.31731
0.161460	1968.76892	312.00000	-1968.76892	-1968.76892	-49.84547
⋮	⋮	⋮	⋮	⋮	⋮

SURFACE 4 - INTEGRATION OF (-AVERAGE PRESSURE*TAN(AVERAGE ANGLE)) TO GET FX4

X	PRESSURE	VELOCITY	INTEGRAND1	INTEGRAND2	SUM
0.136480	1823.69095	480.00000	0.	5003.21576	0.
0.136800	1830.77676	473.00000	5022.65540	1741.94926	1.60414
0.137400	1845.67378	458.00000	1756.12350	685.91782	2.65356
0.138000	1860.64937	442.50000	691.48328	-30.35918	3.06678
0.139000	1883.07016	418.40000	-30.72501	-907.97530	3.03624
0.140000	1901.03282	398.20000	-916.63651	-1267.87556	2.12394
0.141000	1917.22090	379.20000	-1278.67204	-1256.66789	0.85066
0.143000	1945.73315	343.50000	-1275.35663	-1205.80515	-1.68136
⋮	⋮	⋮	⋮	⋮	⋮

SURFACE 4 - INTEGRATION OF (P) TO GET FY4

X	PRESSURE	VELOCITY	INTEGRAND1	INTEGRAND2	SUM
0.136480	1823.69095	480.00000	1823.69095	1823.69095	0.
0.136800	1830.77676	473.00000	1830.77676	1830.77676	0.58472
0.137400	1845.67378	458.00000	1845.67378	1845.67378	1.68765
0.138000	1860.64937	442.50000	1860.64937	1860.64937	2.79955
0.139000	1883.07016	418.40000	1883.07016	1883.07016	4.67141
0.140000	1901.03282	398.20000	1901.03282	1901.03282	6.56346
0.141000	1917.22090	379.20000	1917.22090	1917.22090	8.47259
0.143000	1945.73315	343.50000	1945.73315	1945.73315	12.33554
⋮	⋮	⋮	⋮	⋮	⋮

ANGLE BETWEEN MERIDIONAL-TANGENTIAL AXES AND LIFT-DRAG AXES = 25.0593

SUCTION SURFACE FORCES - FRONT BLADE

X FORCE	Y FORCE	MERIDIONAL FORCE	TANGENTIAL FORCE	DRAG FORCE	LIFT FORCE
188.8227	-296.5217	188.8227	-296.5217	45.4553	-348.5871

PRESSURE SURFACE FORCES - FRONT BLADE

X FORCE	Y FORCE	MERIDIONAL FORCE	TANGENTIAL FORCE	DRAG FORCE	LIFT FORCE
-200.1782	312.9505	-200.1782	312.9505	-48.7834	368.2791

TABLE IV. - Concluded. SELECTED OUTPUT FOR TANDEM BLADE NO. 2 OF NUMERICAL EXAMPLES

SUCTION SURFACE FORCES - REAR BLADE

X FORCE	Y FORCE	MERIDIONAL FORCE	TANGENTIAL FORCE	DRAG FORCE	LIFT FORCE
84.2969	-352.4448	84.2969	-352.4448	-72.9181	-354.9736

PRESSURE SURFACE FORCES - REAR BLADE

X FORCE	Y FORCE	MERIDIONAL FORCE	TANGENTIAL FORCE	DRAG FORCE	LIFT FORCE
-87.0851	365.9404	-87.0851	365.9404	76.1085	368.3798

SUM OF SUCTION SURFACE AND PRESSURE SURFACE FORCES - FRONT BLADE

X FORCE	Y FORCE	MERIDIONAL FORCE	TANGENTIAL FORCE	DRAG FORCE	LIFT FORCE
-11.3555	16.4288	-11.3555	16.4288	-3.3281	19.6921

TOTAL FORCE ON FRONT BLADE = 19.9713
ANGLE WITH RESPECT TO MERIDIONAL AXIS = 124.6521

SUM OF SUCTION SURFACE AND PRESSURE SURFACE FORCES - REAR BLADE

X FORCE	Y FORCE	MERIDIONAL FORCE	TANGENTIAL FORCE	DRAG FORCE	LIFT FORCE
-2.7882	13.4956	-2.7882	13.4956	3.1904	13.4062

TOTAL FORCE ON REAR BLADE = 13.7806
ANGLE WITH RESPECT TO MERIDIONAL AXIS = 101.6732

RATIO OF REAR BLADE FORCES TO FRONT BLADE FORCES

X FORCES	Y FORCES	MERIDIONAL FORCES	TANGENTIAL FORCES	DRAG FORCES	LIFT FORCES
0.2455	0.8215	0.2455	0.8215	-0.9586	0.6808

RATIO OF TOTAL FORCE ON REAR BLADE TO TOTAL FORCE ON FRONT BLADE = 0.6900

SUM OF ALL FRONT AND REAR BLADE FORCES

X FORCE	Y FORCE	MERIDIONAL FORCE	TANGENTIAL FORCE	DRAG FORCE	LIFT FORCE
-14.1438	29.9244	-14.1438	29.9244	-0.1377	33.0983

TOTAL FORCE ON ENTIRE TANDEM BLADE = 33.0986
ANGLE WITH RESPECT TO MERIDIONAL AXIS = 115.2977

OUTPUT

Table IV contains a portion of the output generated for tandem blade number 2 of the numerical examples. Most parts of the output have been abbreviated due to their length.

The first portion of output contains a copy of all the input to the program. The input is shortened here because it was contained in its entirety in table II.

Following the input are the spline curve fits of the X-Y input coordinates of each of the blade surfaces. The X and Y coordinates are listed, followed by the slope, second derivative, and curvature at each point on the surface. From the slopes, angles are computed along the spline curves. These are also printed, along with any input angles which were given by the user. The user should always check the angles and second derivatives of the spline curve to see if a good fit has been obtained. In regions where the spline fit is poor (fluctuating angles or strongly fluctuating second derivatives), the input data should be altered for a subsequent run on the program. Either input data points should be shifted slightly, or points added or subtracted in the critical regions, or angles given as input to be used instead of the spline angles.

The next portion of output contains the summation of components of pressure force along the blade surfaces (see eqs. (2) to (9)) to obtain force contributions in the X and Y directions. A force in the X direction and a force in the Y direction are computed on each of the blade surfaces. The X coordinates of the surface points are listed, together with the static pressure and velocity at the points. The columns labeled "Integrand 1" and "Integrand 2" contain the quantities

$$\pm P_i \tan \frac{\alpha_i + \alpha_{i-1}}{2}$$

and

$$\pm P_i \tan \frac{\alpha_i + \alpha_{i+1}}{2}$$

for the F_X integrations, and the quantities $\pm P_i$ for the F_Y integrations. The column "Sum" contains the cumulative summation of force at each point along the surface, so that the final value of this column is the total force on a surface in the X or Y direction. The differences in the elements in this column indicate the contribution to force from each element of the surface, and help to locate errors in the input when they exist.

The final portion of output lists all the resultant forces on blade surfaces and whole blades. At the beginning of this section, β_{mean} (the angle between the M-θ axis and the

lift-drag axis) is listed. This is followed by lists of forces in the X and Y directions, the M and θ directions, and the lift and drag directions. For a tandem blade, the lift-drag direction is perpendicular and parallel to the mean velocity vector across the overall blade, not across each segment individually. Thus, drag forces listed for the individual segments are not really in the true drag directions for those segments.

Components of force are given first for each of the blade surfaces, and are then combined to give forces on each of the individual blade segments. Total forces are also given on the blade segments and are located with respect to the M or Z axis. For tandem blades, ratios are given for all rear segment forces to front segment forces. Finally, for tandem blades, forces are summed from all four surfaces to give total forces on the overall tandem blade section.

COMPLETE PROGRAM LISTING

```
$IBJOB
$IBFTC LIFTDR

C
C  LIFTDR COMPUTES FORCES DUE TO PRESSURE ON EITHER A SINGLE
C  OR TANDEM BLADE, GIVEN SURFACE GEOMETRY AND SURFACE PRESSURE
C  OR VELOCITY DISTRIBUTIONS
C
      DIMENSION X1(100),X2(100),X3(100),X4(100),Y1(100),Y2(100),
     1Y3(100),Y4(100),P1(100),P2(100),P3(100),P4(100),V1(100),V2(100),
     2V3(100),V4(100),ANG1(100),ANG2(100),ANG3(100),ANG4(100),
     3ANGS1(100),ANGS2(100),ANGS3(100),ANGS4(100),SL(100),SD(100),
     4CU(100),Z(100,2),SUM(100)
C
C  READ AND PRINT INPUT
C
   10 WRITE(6,1000)
      READ (5,1040)
      WRITE(6,1040)
      READ (5,1030) GAM,R,PTZ,TTZ
      WRITE(6,1050) GAM,R,PTZ,TTZ
      READ (5,1030) VRI,VRO,BETAI,BETAO,ALPHMX
      WRITE(6,1060) VRI,VRO,BETAI,BETAO,ALPHMX
      READ (5,1010) KPV,KSURF,NSURF1,NSURF2,NSURF3,NSURF4
      WRITE(6,1070) KPV,KSURF,NSURF1,NSURF2,NSURF3,NSURF4
      IF ((KPV.NE.1.AND.KPV.NE.2).OR.(KSURF.NE.2.AND.KSURF.NE.4)) GO TO
     1320
      IF (KSURF.EQ.2) WRITE(6,1080)
      IF (KSURF.EQ.4) WRITE(6,1100)
      IF (KPV.EQ.1) WRITE(6,1140)
      IF (KPV.EQ.2) WRITE(6,1150)
      READ (5,1020) (X1(I),Y1(I),V1(I),ANG1(I),I=1,NSURF1)
      WRITE(6,1220) (X1(I),Y1(I),V1(I),ANG1(I),I=1,NSURF1)
      IF (KSURF.EQ.2) WRITE(6,1090)
```

```
      IF (KSURF.EQ.4) WRITE(6,1110)
      IF (KPV.EQ.1) WRITE(6,1160)
      IF (KPV.EQ.2) WRITE(6,1170)
      READ (5,1020) (X2(I),Y2(I),V2(I),ANG2(I),I=1,NSURF2)
      WRITE(6,1220) (X2(I),Y2(I),V2(I),ANG2(I),I=1,NSURF2)
      IF (KSURF.EQ.2) GO TO 20
      WRITE(6,1120)
      IF (KPV.EQ.1) WRITE(6,1180)
      IF (KPV.EQ.2) WRITE(6,1190)
      READ (5,1020) (X3(I),Y3(I),V3(I),ANG3(I),I=1,NSURF3)
      WRITE(6,1220) (X3(I),Y3(I),V3(I),ANG3(I),I=1,NSURF3)
      WRITE(6,1130)
      IF (KPV.EQ.1) WRITE(6,1200)
      IF (KPV.EQ.2) WRITE(6,1210)
      READ (5,1020) (X4(I),Y4(I),V4(I),ANG4(I),I=1,NSURF4)
      WRITE(6,1220) (X4(I),Y4(I),V4(I),ANG4(I),I=1,NSURF4)
   20 BETAI= BETAI/57.295780
      BETAO= BETAO/57.295780
      ALPHMX= ALPHMX/57.295780
C
C  FIT SPLINE CURVES TO  X  AND  Y,  COMPUTE SURFACE ANGLES AND
C  CURVATURES,  AND PRINT RESULTS
C
      CALL SPLINE(X1,Y1,NSURF1,SL,SD,CU,ANGS1)
      J= 1
      WRITE(6,1000)
      WRITE(6,1230) J
      WRITE(6,1240) (X1(I),Y1(I),SL(I),SD(I),CU(I),ANGS1(I),ANG1(I),
     1I=1,NSURF1)
      CALL SPLINE(X2,Y2,NSURF2,SL,SD,CU,ANGS2)
      J= 2
      WRITE(6,1230) J
      WRITE(6,1240) (X2(I),Y2(I),SL(I),SD(I),CU(I),ANGS2(I),ANG2(I),
     1I=1,NSURF2)
      IF (KSURF.EQ.2) GO TO 30
      CALL SPLINE(X3,Y3,NSURF3,SL,SD,CU,ANGS3)
      J= 3
      WRITE(6,1230) J
      WRITE(6,1240) (X3(I),Y3(I),SL(I),SD(I),CU(I),ANGS3(I),ANG3(I),
     1I=1,NSURF3)
      CALL SPLINE(X4,Y4,NSURF4,SL,SD,CU,ANGS4)
      J= 4
      WRITE(6,1230) J
      WRITE(6,1240) (X4(I),Y4(I),SL(I),SD(I),CU(I),ANGS4(I),ANG4(I),
     1I=1,NSURF4)
C
C  COMPUTE VELOCITY AND PRESSURE DISTRIBUTIONS ALONG SURFACES
C
   30 RHTZ= PTZ/R/TTZ
      T1= (GAM-1.)/GAM*RHTZ/PTZ/2.
      T2= 1./T1
      T3= GAM/(GAM-1.)
      T4= 1./T3
      IF (KPV.EQ.1) GO TO 50
      DO 40 I=1,NSURF1
   40 P1(I)= PTZ*(1.-T1*V1(I)**2)**T3
      GO TO 70
   50 DO 60 I=1,NSURF1
      P1(I)= V1(I)
```

```
   60 V1(I)= SQRT(T2*(1.-(P1(I)/PTZ)**T4))
      GO TO 90
   70 DO 80 I=1,NSURF2
   80 P2(I)= PTZ*(1.-T1*V2(I)**2)**T3
      GO TO 110
   90 DO 100 I=1,NSURF2
      P2(I)= V2(I)
  100 V2(I)= SQRT(T2*(1.-(P2(I)/PTZ)**T4))
  110 IF (KSURF.EQ.2) GO TO 190
      IF (KPV.EQ.1) GO TO 130
      DO 120 I=1,NSURF3
  120 P3(I)= PTZ*(1.-T1*V3(I)**2)**T3
      GO TO 150
  130 DO 140 I=1,NSURF3
      P3(I)= V3(I)
  140 V3(I)= SQRT(T2*(1.-(P3(I)/PTZ)**T4))
      GO TO 170
  150 DO 160 I=1,NSURF4
  160 P4(I)= PTZ*(1.-T1*V4(I)**2)**T3
      GO TO 190
  170 DO 180 I=1,NSURF4
      P4(I)= V4(I)
  180 V4(I)= SQRT(T2*(1.-(P4(I)/PTZ)**T4))
C
C  INTEGRATE PRESSURE DISTRIBUTIONS TO OBTAIN COMPONENTS OF X AND Y
C  FORCES, AND PRINT RESULTS
C
  190 NM= NSURF1-1
      IF (ANG1(1).EQ.0.) ANG1(1)=ANGS1(1)
      IF (ANG1(2).EQ.0.) ANG1(2)=ANGS1(2)
      ANG1(1)= ANG1(1)/57.295780
      ANG1(2)= ANG1(2)/57.295780
      Z(1,1)= 0.
      Z(1,2)= P1(1)*TAN((ANG1(1)+ANG1(2))/2.)
      DO 200 I=2,NM
      IF (ANG1(I+1).EQ.0.) ANG1(I+1)=ANGS1(I+1)
      ANG1(I+1)= ANG1(I+1)/57.295780
      Z(I,1)=  P1(I)*TAN((ANG1(I)+ANG1(I-1))/2.)
  200 Z(I,2)=  P1(I)*TAN((ANG1(I)+ANG1(I+1))/2.)
      Z(NSURF1,1)=  P1(NSURF1)*TAN((ANG1(NSURF1)+ANG1(NM))/2.)
      Z(NSURF1,2)= 0.
      CALL TINTGR(X1,Z,NSURF1,SUM)
      FX1= SUM(NSURF1)
      J= 1
      WRITE(6,1000)
      WRITE(6,1250) J,J
      WRITE(6,1290)
      WRITE(6,1300) (X1(I),P1(I),V1(I),Z(I,1),Z(I,2),SUM(I),I=1,NSURF1)
      DO 210 I=1,NSURF1
      Z(I,1)= -P1(I)
  210 Z(I,2)= -P1(I)
      CALL TINTGR(X1,Z,NSURF1,SUM)
      FY1= SUM(NSURF1)
      WRITE(6,1260) J,J
      WRITE(6,1290)
      WRITE(6,1300) (X1(I),P1(I),V1(I),Z(I,1),Z(I,2),SUM(I),I=1,NSURF1)
      NM= NSURF2-1
      IF (ANG2(1).EQ.0.) ANG2(1)=ANGS2(1)
```

```
      IF (ANG2(2).EQ.0.) ANG2(2)=ANGS2(2)
      ANG2(1)= ANG2(1)/57.295780
      ANG2(2)= ANG2(2)/57.295780
      Z(1,1)= 0.
      Z(1,2)= -P2(1)*TAN((ANG2(1)+ANG2(2))/2.)
      DO 220 I=2,NM
      IF (ANG2(I+1).EQ.0.) ANG2(I+1)=ANGS2(I+1)
      ANG2(I+1)= ANG2(I+1)/57.295780
      Z(I,1)= -P2(I)*TAN((ANG2(I)+ANG2(I-1))/2.)
  220 Z(I,2)= -P2(I)*TAN((ANG2(I)+ANG2(I+1))/2.)
      Z(NSURF2,1)= -P2(NSURF2)*TAN((ANG2(NSURF2)+ANG2(NM))/2.)
      Z(NSURF2,2)= 0.
      CALL TINTGR(X2,Z,NSURF2,SUM)
      FX2= SUM(NSURF2)
      J= 2
      WRITE(6,1270) J,J
      WRITE(6,1290)
      WRITE(6,1300) (X2(I),P2(I),V2(I),Z(I,1),Z(I,2),SUM(I),I=1,NSURF2)
      DO 230 I=1,NSURF2
      Z(I,1)= P2(I)
  230 Z(I,2)= P2(I)
      CALL TINTGR(X2,Z,NSURF2,SUM)
      FY2= SUM(NSURF2)
      WRITE(6,1280) J,J
      WRITE(6,1290)
      WRITE(6,1300) (X2(I),P2(I),V2(I),Z(I,1),Z(I,2),SUM(I),I=1,NSURF2)
      IF (KSURF.EQ.2) GO TO 280
      NM= NSURF3-1
      IF (ANG3(1).EQ.0.) ANG3(1)=ANGS3(1)
      IF (ANG3(2).EQ.0.) ANG3(2)=ANGS3(2)
      ANG3(1)= ANG3(1)/57.295780
      ANG3(2)= ANG3(2)/57.295780
      Z(1,1)= 0.
      Z(1,2)= P3(1)*TAN((ANG3(1)+ANG3(2))/2.)
      DO 240 I=2,NM
      IF (ANG3(I+1).EQ.0.) ANG3(I+1)=ANGS3(I+1)
      ANG3(I+1)= ANG3(I+1)/57.295780
      Z(I,1)=  P3(I)*TAN((ANG3(I)+ANG3(I-1))/2.)
  240 Z(I,2)=  P3(I)*TAN((ANG3(I)+ANG3(I+1))/2.)
      Z(NSURF3,1)=  P3(NSURF3)*TAN((ANG3(NSURF3)+ANG3(NM))/2.)
      Z(NSURF3,2)= 0.
      CALL TINTGR(X3,Z,NSURF3,SUM)
      FX3= SUM(NSURF3)
      J= 3
      WRITE(6,1250) J,J
      WRITE(6,1290)
      WRITE(6,1300) (X3(I),P3(I),V3(I),Z(I,1),Z(I,2),SUM(I),I=1,NSURF3)
      DO 250 I=1,NSURF3
      Z(I,1)= -P3(I)
  250 Z(I,2)= -P3(I)
      CALL TINTGR(X3,Z,NSURF3,SUM)
      FY3= SUM(NSURF3)
      WRITE(6,1260) J,J
      WRITE(6,1290)
      WRITE(6,1300) (X3(I),P3(I),V3(I),Z(I,1),Z(I,2),SUM(I),I=1,NSURF3)
      NM= NSURF4-1
      IF (ANG4(1).EQ.0.) ANG4(1)=ANGS4(1)
      IF (ANG4(2).EQ.0.) ANG4(2)=ANGS4(2)
```

```
      ANG4(1)= ANG4(1)/57.295780
      ANG4(2)= ANG4(2)/57.295780
      Z(1,1)= 0.
      Z(1,2)= -P4(1)*TAN((ANG4(1)+ANG4(2))/2.)
      DO 260 I=2,NM
      IF (ANG4(I+1).EQ.0.) ANG4(I+1)=ANGS4(I+1)
      ANG4(I+1)= ANG4(I+1)/57.295780
      Z(I,1)= -P4(I)*TAN((ANG4(I)+ANG4(I-1))/2.)
  260 Z(I,2)= -P4(I)*TAN((ANG4(I)+ANG4(I+1))/2.)
      Z(NSURF4,1)= -P4(NSURF4)*TAN((ANG4(NSURF4)+ANG4(NM))/2.)
      Z(NSURF4,2)= 0.
      CALL TINTGR(X4,Z,NSURF4,SUM)
      FX4= SUM(NSURF4)
      J= 4
      WRITE(6,1270) J,J
      WRITE(6,1290)
      WRITE(6,1300) (X4(I),P4(I),V4(I),Z(I,1),Z(I,2),SUM(I),I=1,NSURF4)
      DO 270 I=1,NSURF4
      Z(I,1)= P4(I)
  270 Z(I,2)= P4(I)
      CALL TINTGR(X4,Z,NSURF4,SUM)
      FY4= SUM(NSURF4)
      WRITE(6,1280) J,J
      WRITE(6,1290)
      WRITE(6,1300) (X4(I),P4(I),V4(I),Z(I,1),Z(I,2),SUM(I),I=1,NSURF4)
C
C  ROTATE  X AND Y  FORCES TO OBTAIN COMPONENTS OF
C  MERIDIONAL AND TANGENTIAL FORCES
C
  280 CALPH= COS(ALPHMX)
      SALPH= SIN(ALPHMX)
      FM1= FX1*CALPH-FY1*SALPH
      FT1= FX1*SALPH+FY1*CALPH
      FM2= FX2*CALPH-FY2*SALPH
      FT2= FX2*SALPH+FY2*CALPH
      IF (KSURF.EQ.2) GO TO 290
      FM3= FX3*CALPH-FY3*SALPH
      FT3= FX3*SALPH+FY3*CALPH
      FM4= FX4*CALPH-FY4*SALPH
      FT4= FX4*SALPH+FY4*CALPH
C
C  ROTATE MERIDIONAL AND TANGENTIAL FORCES TO OBTAIN COMPONENTS OF
C  LIFT AND DRAG FORCES
C
  290 VMI= VRI*COS(BETAI)
      VTI= VRI*SIN(BETAI)
      VMO= VRO*COS(BETAO)
      VTO= VRO*SIN(BETAO)
      BETAM= ATAN((VTI+VTO)/(VMI+VMO))*57.295780
      WRITE(6,1310) BETAM
      BETAM= BETAM/57.295780
      CBETA= COS(BETAM)
      SBETA= SIN(BETAM)
      FD1=  FM1*CBETA+FT1*SBETA
      FL1= -FM1*SBETA+FT1*CBETA
      FD2=  FM2*CBETA+FT2*SBETA
      FL2= -FM2*SBETA+FT2*CBETA
      IF (KSURF.EQ.2) WRITE(6,1330)
```

```
      IF (KSURF.EQ.4) WRITE(6,1340)
      WRITE(6,1320) FX1,FY1,FM1,FT1,FD1,FL1
      IF (KSURF.EQ.2) WRITE(6,1350)
      IF (KSURF.EQ.4) WRITE(6,1360)
      WRITE(6,1320) FX2,FY2,FM2,FT2,FD2,FL2
      IF (KSURF.EQ.2) GO TO 300
      FD3=  FM3*CBETA+FT3*SBETA
      FL3= -FM3*SBETA+FT3*CBETA
      FD4=  FM4*CBETA+FT4*SBETA
      FL4= -FM4*SBETA+FT4*CBETA
      WRITE(6,1370)
      WRITE(6,1320) FX3,FY3,FM3,FT3,FD3,FL3
      WRITE(6,1380)
      WRITE(6,1320) FX4,FY4,FM4,FT4,FD4,FL4
C
C  SUM FORCES ON BLADE SEGMENTS,  RATIO FORCES FOR TANDEM BLADES,
C  AND COMPUTE TOTAL FORCES ON BLADE SECTION
C
C  TWO SURFACES
  300 FX12= FX1+FX2
      FY12= FY1+FY2
      FM12= FM1+FM2
      FT12= FT1+FT2
      FD12= FD1+FD2
      FL12= FL1+FL2
      IF (KSURF.EQ.2) WRITE(6,1390)
      IF (KSURF.EQ.4) WRITE(6,1400)
      WRITE(6,1320) FX12,FY12,FM12,FT12,FD12,FL12
      TF12= SQRT(FM12**2+FT12**2)
      ATF12M= ATAN(FT12/FM12)*57.295780
      IF (ATF12M.LT.0.) ATF12M= 180.+ATF12M
      IF (KSURF.EQ.2) WRITE(6,1410) TF12
      IF (KSURF.EQ.4) WRITE(6,1420) TF12
      WRITE(6,1430) ATF12M
      IF (KSURF.EQ.4) GO TO 310
      GO TO 10
C  FOUR SURFACES
  310 FX34= FX3+FX4
      FY34= FY3+FY4
      FM34= FM3+FM4
      FT34= FT3+FT4
      FD34= FD3+FD4
      FL34= FL3+FL4
      WRITE(6,1440)
      WRITE(6,1320) FX34,FY34,FM34,FT34,FD34,FL34
      TF34= SQRT(FM34**2+FT34**2)
      ATF34M= ATAN(FT34/FM34)*57.295780
      IF (ATF34M.LT.0.) ATF34M= 180.+ATF34M
      WRITE(6,1450) TF34
      WRITE(6,1430) ATF34M
      FXRAT= FX34/FX12
      FYRAT= FY34/FY12
      FMRAT= FM34/FM12
      FTRAT= FT34/FT12
      FDRAT= FD34/FD12
      FLRAT= FL34/FL12
      WRITE(6,1460) FXRAT,FYRAT,FMRAT,FTRAT,FDRAT,FLRAT
      TFRAT= TF34/TF12
```

```
      WRITE(6,1470) TFRAT
      FX14= FX12+FX34
      FY14= FY12+FY34
      FM14= FM12+FM34
      FT14= FT12+FT34
      FD14= FD12+FD34
      FL14= FL12+FL34
      WRITE(6,1480)
      WRITE(6,1320) FX14,FY14,FM14,FT14,FD14,FL14
      TF14= SQRT(FM14**2+FT14**2)
      ATF14M= ATAN(FT14/FM14)*57.295780
      IF (ATF14M.LT.0.) ATF14M= 180.+ATF14M
      WRITE(6,1490) TF14
      WRITE(6,1430) ATF14M
      GO TO 10
  320 WRITE(6,1500)
      STOP
C
C  FORMAT STATEMENTS
C
 1000 FORMAT(1H1///)
 1010 FORMAT(16I5)
 1020 FORMAT(4F10.5)
 1030 FORMAT(8F10.5)
 1040 FORMAT(80H
     1                                    )
 1050 FORMAT(//6X,3HGAM,9X,1HR,11X,3HPTZ,8X,3HTTZ/3X,F7.3,3X,F9.2,3X,
     1F10.2,2X,F9.2//)
 1060 FORMAT(6X,3HVRI,9X,3HVRO,8X,5HBETAI,7X,5HBETAO,7X,6HALPHMX/3X,
     1F10.5,2X,F10.5,1X,F8.3,4X,F8.3,5X,F8.3//)
 1070 FORMAT(6X,3HKPV,8X,5HKSURF,7X,6HNSURF1,6X,6HNSURF2,6X,6HNSURF3,6X,
     16HNSURF4/6X,I2,10X,I2,10X,I3,9X,I3,9X,I3,9X,I3//)
 1080 FORMAT(/5X,15HSUCTION SURFACE)
 1090 FORMAT(/5X,16HPRESSURE SURFACE)
 1100 FORMAT(/5X,29HSUCTION SURFACE - FRONT BLADE)
 1110 FORMAT(/5X,30HPRESSURE SURFACE - FRONT BLADE)
 1120 FORMAT(/5X,28HSUCTION SURFACE - REAR BLADE)
 1130 FORMAT(/5X,29HPRESSURE SURFACE - REAR BLADE)
 1140 FORMAT(8X,2HX1,11X,2HY1,11X,2HP1,10X,4HANG1)
 1150 FORMAT(8X,2HX1,11X,2HY1,11X,2HV1,10X,4HANG1)
 1160 FORMAT(8X,2HX2,11X,2HY2,11X,2HP2,10X,4HANG2)
 1170 FORMAT(8X,2HX2,11X,2HY2,11X,2HV2,10X,4HANG2)
 1180 FORMAT(8X,2HX3,11X,2HY3,11X,2HP3,10X,4HANG3)
 1190 FORMAT(8X,2HX3,11X,2HY3,11X,2HV3,10X,4HANG3)
 1200 FORMAT(8X,2HX4,11X,2HY4,11X,2HP4,10X,4HANG4)
 1210 FORMAT(8X,2HX4,11X,2HY4,11X,2HV4,10X,4HANG4)
 1220 FORMAT(3X,F10.6,3X,F10.6,3X,F10.4,3X,F10.4)
 1230 FORMAT(///5X,8HSURFACE ,I1,20H - SPLINE FIT OF X-Y,42X,6HSPLINE,
     19X,5HINPUT/8X,1HX,11X,1HY,10X,5HSLOPE,7X,11HSEC. DERIV.,7X,
     29HCURVATURE,6X,5HANGLE,10X,5HANGLE)
 1240 FORMAT((3X,F10.6,2X,F10.6,1X,F12.5,1X,F15.5,4X,F12.5,3X,F9.4,6X,
     1F9.4))
 1250 FORMAT(///5X,8HSURFACE ,I1,65H - INTEGRATION OF (AVERAGE PRESSURE*
     1TAN(AVERAGE ANGLE)) TO GET FX,I1)
 1260 FORMAT(///5X,8HSURFACE ,I1,32H - INTEGRATION OF (-P) TO GET FY,I1)
 1270 FORMAT(///5X,8HSURFACE ,I1,66H - INTEGRATION OF (-AVERAGE PRESSURE
     1*TAN(AVERAGE ANGLE)) TO GET FX,I1)
 1280 FORMAT(///5X,8HSURFACE ,I1,31H - INTEGRATION OF (P) TO GET FY,I1)
```

```
1290 FORMAT(8X,1HX,10X,8HPRESSURE,6X,8HVELOCITY,8X,10HINTEGRAND1,7X,
    110HINTEGRAND2,11X,3HSUM)
1300 FORMAT((3X,F10.6,4X,F11.5,4X,F10.5,3X,F14.5,3X,F14.5,6X,F11.5))
1310 FORMAT(1H1///4X,61HANGLE BETWEEN MERIDIONAL-TANGENTIAL AXES AND LI
    1FT-DRAG AXES =,F9.4///////)
1320 FORMAT(12X,1HX,14X,1HY,9X,10HMERIDIONAL,5X,10HTANGENTIAL,8X,4HDRAG
    1,11X,4HLIFT/6(10X,5HFORCE)/1X,6(4X,F11.4)//)
1330 FORMAT(4X,22HSUCTION SURFACE FORCES)
1340 FORMAT(4X,36HSUCTION SURFACE FORCES - FRONT BLADE)
1350 FORMAT(4X,23HPRESSURE SURFACE FORCES)
1360 FORMAT(4X,37HPRESSURE SURFACE FORCES - FRONT BLADE)
1370 FORMAT(4X,35HSUCTION SURFACE FORCES - REAR BLADE)
1380 FORMAT(4X,36HPRESSURE SURFACE FORCES - REAR BLADE)
1390 FORMAT(/////4X,50HSUM OF SUCTION SURFACE AND PRESSURE SURFACE FORC
    1ES)
1400 FORMAT(/////4X,64HSUM OF SUCTION SURFACE AND PRESSURE SURFACE FORC
    1ES - FRONT BLADE)
1410 FORMAT(9X,22HTOTAL FORCE ON BLADE =,F11.4)
1420 FORMAT(9X,28HTOTAL FORCE ON FRONT BLADE =,F11.4)
1430 FORMAT(9X,39HANGLE WITH RESPECT TO MERIDIONAL AXIS =,F11.4////)
1440 FORMAT(4X,63HSUM OF SUCTION SURFACE AND PRESSURE SURFACE FORCES -
    1REAR BLADE)
1450 FORMAT(9X,27HTOTAL FORCE ON REAR BLADE =,F11.4)
1460 FORMAT(1H1///4X,48HRATIO OF REAR BLADE FORCES TO FRONT BLADE FORCE
    1S/12X,1HX,14X,1HY,9X,10HMERIDIONAL,5X,10HTANGENTIAL,8X,4HDRAG,11X,
    24HLIFT/6(9X,6HFORCES)/1X,6(4X,F11.4)//)
1470 FORMAT(9X,66HRATIO OF TOTAL FORCE ON REAR BLADE TO TOTAL FORCE ON
    1FRONT BLADE =,F10.4///////)
1480 FORMAT(4X,38HSUM OF ALL FRONT AND REAR BLADE FORCES)
1490 FORMAT(9X,36HTOTAL FORCE ON ENTIRE TANDEM BLADE =,F11.4)
1500 FORMAT(///1X,29HERROR IN INPUT - KPV OR KSURF)
     END
```

```
$IBFTC SPLIN

      SUBROUTINE SPLINE(X,Y,N,DYDX,D2YDX2,CURV,ANG)
C
C  SPLINE FITS A SPLINE CURVE TO X AND Y,  AND CALCULATES FIRST AND
C  SECOND DERIVATIVES, CURVATURES, AND ANGLES AT THE SPLINE POINTS
C
      DIMENSION X(N),Y(N),DYDX(N),D2YDX2(N),CURV(N),ANG(N)
      DIMENSION G(100),H(100)
      G(1)= -2.0
      H(1)= 0.
      N1= N-1
      IF (N1.LT.2) GO TO 20
      DO 10 I=2,N1
      A= (X(I)-X(I-1))/6.
      B= (X(I+1)-X(I))/6.
      C= 2.*(A+B)-A*G(I-1)
      D= (Y(I+1)-Y(I))/(X(I+1)-X(I))-(Y(I)-Y(I-1))/(X(I)-X(I-1))
      G(I)= B/C
   10 H(I)= (D-A*H(I-1))/C
```

```
20 D2YDX2(N)= H(N1)/(.5+G(N1))
   DO 30 I=2,N
   K= N+1-I
30 D2YDX2(K)= H(K)-G(K)*D2YDX2(K+1)
   DYDX(1)= (X(1)-X(2))/6.*(2.*D2YDX2(1)+D2YDX2(2))+(Y(2)-Y(1))/(X(2)
  1-X(1))
   DO 40 I=2,N
40 DYDX(I)= (X(I)-X(I-1))/6.*(2.*D2YDX2(I)+D2YDX2(I-1))+(Y(I)-Y(I-1))
  1/(X(I)-X(I-1))
   DO 50 I=1,N
   CURV(I)= D2YDX2(I)/(1.+DYDX(I)**2)**1.5
50 ANG(I)= ATAN(DYDX(I))*57.295780
   RETURN
   END
```

```
$IBFTC TINTG

      SUBROUTINE TINTGR(X,Y,N,SUM)
C
C  TINTGR INTEGRATES THE SET OF DATA POINTS X-Y USING THE
C  TRAPAZOIDAL RULE
C
      DIMENSION X(100),Y(100,2),SUM(100)
      SUM(1)= 0.
      DO 10 I=2,N
   10 SUM(I)= SUM(I-1)+(Y(I,1)+Y(I-1,2))*(X(I)-X(I-1))/2.
      RETURN
      END
```

Lewis Research Center,

National Aeronautics and Space Administration,

Cleveland, Ohio, July 7, 1970,

126-15.

APPENDIX - SYMBOLS

F	force on blade section or blade surface, per unit of blade height, lbf/ft; N/m
M	distance in meridional direction, ft; m
P	pressure, lbf/ft^2; N/m^2
R	distance in radial direction, ft; m
T	temperature, $^{\circ}R$; K
V	relative velocity (figs. 3 and 6), ft/sec; m/sec
V_{mean}	mean relative velocity across blade section (fig. 6), ft/sec; m/sec
X	distance in X (input) direction, ft; m
Y	distance in Y (input) direction, ft; m
Z	distance in axial direction, ft; m
α	blade surface angle with respect to the X axis (fig. 5), deg
α_{MX}	angle between meridional axis and X axis of input (fig. 2), deg
β	relative flow angle with respect to meridional or axial direction (figs. 3 and 6), deg
β_{mean}	mean flow angle across blade section (fig. 6), deg
γ	ratio of specific heats
θ	distance in tangential direction, rad
ρ	density, $slug/ft^3$; kg/m^3

Subscripts:

D	in the drag force direction (parallel to direction of mean velocity)
i	at a local point
in	at the blade inlet
L	in the lift force direction (perpendicular to direction of mean velocity)
M	in the meridional direction
out	at the blade outlet
p	pressure surface value
s	suction surface value
tot	total force
X	in the X (input) direction
Y	in the Y (input) direction
Z	in the axial direction
θ	in the tangential direction
1, 2, 3, 4	identification of blade surfaces 1, 2, 3, or 4

Superscript:

'	total or stagnation value

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